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The effect of grain size on the elevated temperature plastic properties of some high-purity aluminum alloys

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THE EFFECT OF GRAIN SIZE ON THE ELEVATED
TEMPERATURE PLASTIC PROPERTIES OF SOME
HIGH-PURITY ALUMINUM ALLOYS

EARL CURTIS VICARS

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THE EFFECT OG GRAIN SIZE ON THE
ELEVATED TEMPERATURE PLASTIC
PROPERTIES OF SOME HIGH-PURITY
ALUMINUM ALLOYS

EARL CURTIS VICARS

The Effect of Grain Size
on the Elevated Temperature Plastic Properties
of Some High-Purity Aluminum Alloys

By

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B. S. (Purdue University) 1942
M. S. (University of California) 1951

THESIS

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of the

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ABSTRACT

The creep properties of coarse and fine grained pure aluminum, aluminum-magnesium solid solution alloy and aluminum-copper dispersion alloy were investigated over the temperature range 422^0K to 528^0K. At low temperatures and high stresses the fine grained materials were superior to the coarse grained materials of the same composition. At approximately 528^0K, however, the creep behavior of the fine and coarse grained material for any given composition was essentially indistinguishable. An energy of activation for the creep process for pure aluminum, aluminum-magnesium solid solution alloy and aluminum-copper dispersion alloy was determined to be 34,000, 42,000 and 37,000 cal/mol respectively.

INTRODUCTION

Although the effect of grain size on the creep properties of metals has been extensively investigated, a complete isolation of the true grain boundary effect has probably not yet been achieved.

It has been generally reported[1-7] that at higher temperatures and lower strain rates coarse grained metals creep less rapidly than fine grained metals, whereas at low testing temperatures and high strain rates, fine grained materials are superior in creep resistance to coarse grained materials. Other evidence exists, however, which yields contrary conclusions[6]. Perhaps one cause of the uncertainty concerning the influence of grain size on the creep of metals is due to the complexity of the alloys investigated. For instance, the difference in creep properties attributed to grain size might in part be due to other metallurgical processes or states present during, or preceding creep such as precipitation, over-aging, grain growth, recrystallization, solid solution alloying and other factors which might differ due to the different treatments used in obtaining the various grain sizes. Investigations on 2 S-O aluminum alloy at this University[5] have revealed that higher annealing temperatures, in the absence of grain growth, increase the creep resistance of 2 S-O Hence annealing, which induces greater grain perfection, is, in itself, an important factor in determining the creep resistance of metals. Therefore in order to attempt to isolate the effect of grain size on creep it would be desirable to first understand how this factor affects the creep properties of a pure metal.

A very complete experimental investigation on the effect of grain size on creep behavior at elevated temperatures has been made by Servi

and Grant[7] on aluminum of very high purity. They obtained constant
stress creep data of 99.995% pure aluminum for two different grain sizes
tested at temperatures between 200^0F and 1100^0F. These data are record-
ed in Figure 1. In a recent report, Sherby and Dorn[8] demonstrated the
validity, above 300^0F, of the Zener-Hollomon equation $\sigma = \sigma(\dot{\epsilon} \, e^{\frac{\Delta H}{RT}})$
relating the applied stress to the strain rate and temperature. This law
was found valid for dilute alpha solid solution alloys of aluminum wherein
the activation energy, ΔH, was found to be approximately a constant equal
to 35,800 calories/mole. Accordingly, Servi and Grant's data (above 300^0F)
shown in Figure 1 can be reduced to two separate creep curves, one for the
fine grained material and one for the coarse grained material, when the
creep stress σ is plotted as a function of $\ln(\dot{\epsilon}_s \, e^{\frac{17900}{T}})$. The validity
of this procedure is shown graphically in Figure 2.

Servi and Grant employed a very wide range in grain sizes (coarse
grained material was 2 mm in diameter whereas the fine grained material
had grains 0.05 mm in diameter) as well as wide ranges of temperature
and stress of creep testing. It will be observed that the creep resistance
of the fine grained aluminum is slightly superior to that of the coarse
grained aluminum for values of $\ln(\dot{\epsilon}_s \, e^{\frac{17900}{T}})$ greater than 29.0, whereas
at lower values of this parameter the coarse grained aluminum exhibited
superior creep resistance. The effect of grain size on the creep resist-
ance, however, is very small. This relatively small difference in creep
properties might well be ascribable to differences in annealing to achieve
the dissimilar grain sizes rather than to grain size per se.

A grain size effect, however, cannot yet be disqualified. There
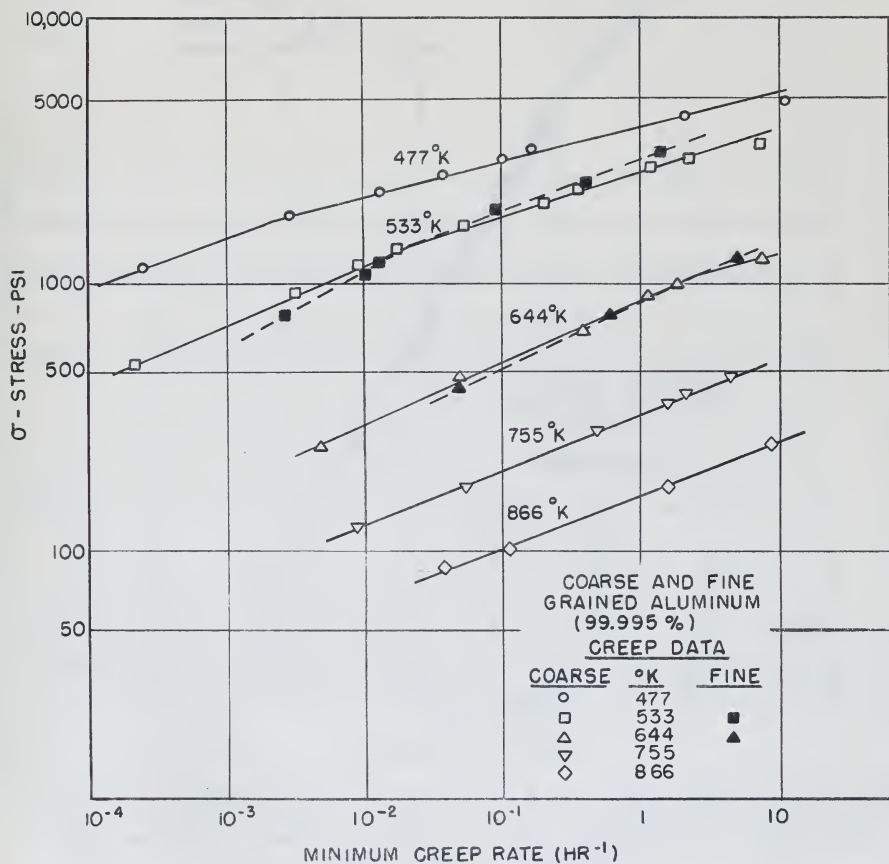are several important processes taking place during creep at elevated

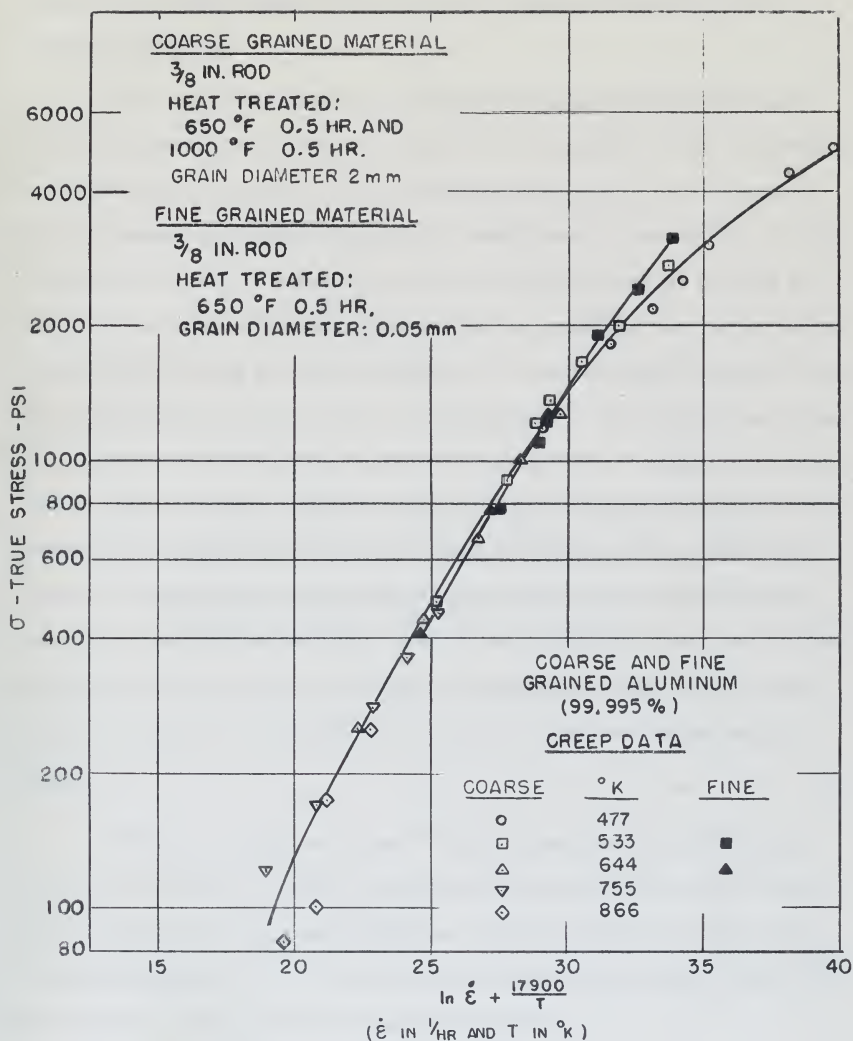FIG. I LOG-LOG PLOT OF STRESS VERSUS MINIMUM CREEP RATE.
(DATA FROM SERVI AND GRANT[7])

FIG. 2 CORRELATION OF CREEP DATA OF HIGH PURITY ALUMINUM AT VARIOUS TEMPERATURES BY THE EQUATION: $\sigma \equiv \sigma\left(\dot{\epsilon}\, e^{\frac{17900}{T}}\right)$

(DATA BY SERVI AND GRANT[7])

temperatures which might hint at the role of grain size on the creep behavior of metals.

1. It is well known that grain boundary regions behave in a quasi-viscous manner at high temperatures[9]; for example, it has been demonstrated that at suitably elevated temperatures and low strain rates, grain boundaries in metals experience shear displacements[10]; thus the creep rate under such conditions is not only determined by the slip processes of deformation taking place within the grain but also on the shear displacements along the grain boundary. A coarse grained material, containing less grain boundary per unit volume than a fine grained material, would experience less grain boundary shear and hence might contribute less to the creep rate, yielding in turn a more creep resistant material. In the case of alloyed materials, it might be anticipated that the solute atoms or intermetallic compounds present would tend to prevent grain boundary shearing and thus inversion in the creep resistance due to grain size should not take place until higher temperatures and slower strain rates are employed in comparison to those for the corresponding pure metal.

2. Recently Chang and Grant[11] have shown very clearly that in elevated temperature creep of aluminum an important process is one of grain boundary shearing and migration. They tested high purity coarse grained aluminum at very low stresses and high temperatures (700-900°F) and obtained a creep curve as shown in Figure 3.
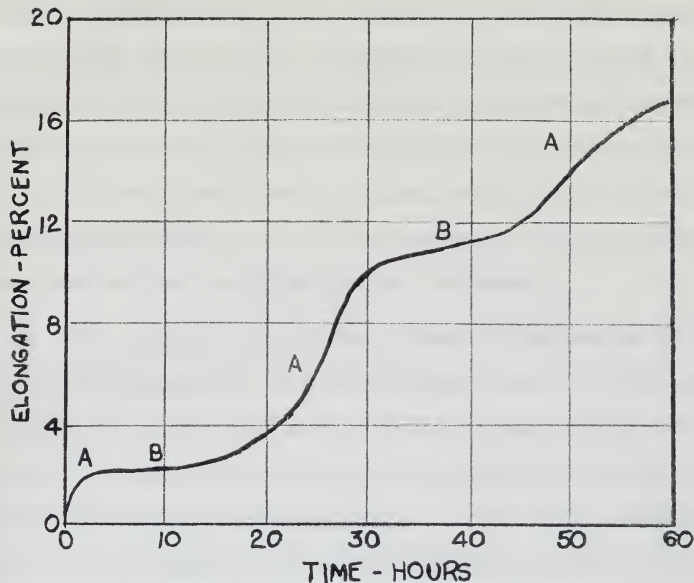
FIG. 3 CREEP CURVE BETWEEN TWO REFERENCE
MARKS ACROSS A GRAIN BOUNDARY

The strains were measured between two markers on opposite sides of a
grain boundary. A microscope was used to observe the strain-time
relationship as well as to note metallurgical changes that might have been
taking place during creep. The resulting creep curve was explained as a
consequence of a two stage process, one of grain boundary shearing
(stage B) followed by grain boundary migration (stage A). Whenever
boundary shearing took place it contributed to the creep strain and this
would be followed by a period of essentially no creep during which time
the grain boundary was observed to migrate to a new position. Shearing
would then take place anew.

These important contributions by Chang and Grant suggest another
reason for the supposed superior creep resistance of coarse grained

materials. A fine grained metal is inherently less stable than a coarse grained metal; for example, grain growth will occur earlier and more rapidly for a fine grained specimen than a coarse grained one when heated to high temperatures. Thus stage A (grain boundary migration) in Chang and Grant's creep process will take place with greater ease for a fine grained material than for a coarse grained one, thereby inducing faster creep rates for the case of fine grained specimens.

3. The formation of strain free elements from bent lattice planes, without recrystallization, is termed polygonization[12]. This can occur by heating a cold-deformed metal crystal to a high temperature. The process of polygonization has been recently utilized to explain the mechanism of creep at elevated temperatures. Thus, some investigators[13,14] assume that the creep process at elevated temperatures is associated with polygonization of grains into perfect strain-free subgrains. Chang and Grant[11] as well as other investigators have shown that polygonization tends to occur near the grain boundary first where the greatest lattice distortion or bending has taken place. This then suggests yet another reason for the superior creep resistance of coarse grained metals to fine grained metals. If creep at elevated temperatures is primarily a result of polygonization then it becomes clear that coarse grains, containing less grain boundary area per unit volume, would polygonize less and thus be stronger in creep than fine grains.

The results of another recent creep investigation on aluminum alloys by British scientists[15] revealed that although polygonization is not seriously inhibited by solid solution alloying, the presence of a

precipitate greatly retards the formation of polygonized blocks during creep at the temperature studied (300^0C).

Hence it would seem to follow that the presence of a precipitate would demand that a higher temperature be attained before polygonization would occur in the precipitate alloy when compared with the temperature for polygonization in a pure metal. Thus the inversion due to the grain size effect for the precipitate alloy could be expected to occur only after temperatures high enough to permit polygonization have been attained.

It should be noted however that an inversion at a higher temperature for the precipitate alloy would not necessarily prove that polygonization alone is the cause for the differences in creep properties of coarse and fine grained materials. For instance, the presence of a precipitate could conceivably decrease the rate of migration of the grain boundary in the model proposed by Chang and Grant. In this case, a higher temperature would also be required before the boundary could migrate to a shear position.

In view of the previous observations on the effect of solid solution alloying and the presence of a precipitate on the formation of polygonized blocks, an investigation of the creep properties of coarse and fine grained pure metal, a solid solution alloy and a dispersion alloy should contribute to an understanding of not only the effect of polygonization during the creep process but also the various other processes outlined herein.

MATERIALS FOR TEST

The materials selected for the present investigation follow in part a pattern previously established in various recent studies of the

plastic properties of aluminum, its solid solution and dispersion type alloys. For the purpose of this study pure aluminum, an aluminum-magnesium solid solution alloy containing 1.10 atomic percent magnesium and an aluminum-copper dispersion alloy containing 1.18 atomic percent copper were chosen as representative of their respective alloy types. The materials were available in 0.100 inch thick sheet. Each material was homogenized, cold rolled and heat treated to obtain the appropriate grain sizes and dispersions. Extreme care was exercised in the treatment of the aluminum-copper alloys in order to maintain the same type and degree of dispersion. The schedule for the various treatments used is shown in Table I.

TABLE I
Processing Schedule

Material	Homogenization Treatment	Cold Rolling Treatment	Grain Size Treatment	Dispersion Treatment
99.99% Pure Al Fine	As received	30% to 0.070 inch	635°F, 1 hr, AC*	————
Coarse	As received	"	860°F, 30 min, AC	————
1.10 Atomic % Mg in Aluminum Fine	820°F, 8 days, AC	30% to 0.070 inch	804°F, 45 sec, AC	————
Coarse	"	"	802°F, 10 min, AC	————
1.18 Atomic% Cu in Aluminum Fine	1004°F, 3 days AC	30% to 0.070 inch	880°F, 25 sec, WQ*	851°F, 15 min, WQ 662°F, 3hrs, FC* to 581°F, 2 days, AC Machine 581°F, 2 days,
Coarse	"	"	1004°F, 3 min, WQ	"

*AC Air cooled   *WQ Water quench   *FC Furnace cooled

All heat treatments were effected in a salt bath furnace controlled to
± 2°F. Grain size measurements were made by taking a linear count of the
number of grains across the width of the specimen viewed at 100 magnifica-
tion. The average of three counts was taken as the grain size.

Chemical analyses of the various test materials were as shown below:

Alloying Element	Atomic Percent	Wt. Percent of Residual Impurities				
		Si	Fe	Cu	Mg	Mn
Aluminum	99.99	0.003	0.003	0.006	0.001	———
Magnesium	1.10	0.004	0.004	0.007	———	———
Copper	1.18	0.002	0.002	———	———	trace

EXPERIMENTAL EQUIPMENT AND TECHNIQUE

All creep specimens were machined with the tensile axes in the rolling
direction of the 0.070 inch sheet stock. The gage section was 2 inches long
and 0.500 inches wide with a reduced section of 3.50 inches.

Creep strains were measured by means of a rack and pinion type extenso-
meter with a sensitivity of 0.005 inches per division. Strains of approxi-
mately 0.00025 were detectable by estimating readings to 1/10 of a division.

Creep furnace temperatures of $422°K$, $477°K$ and $528°K$ were employed
in this investigation. The $422°K$ and $477°K$ temperatures were attained by
the use of furnaces containing boiling glycol-water solutions, the vapors
of which were condensed and returned to maintain fixed compositions and
boiling temperatures. The $528°K$ temperature was attained by use of a
specially prepared constant boiling temperature "Dow-therm A" solution.
The creep specimens were suspended within their respective furnaces in

vertical tubes having an air atmosphere and end seals were used to prevent convection of air through the tubes. Specimens were maintained at constant temperature within $\pm 1^{\circ}$K throughout the tests.

Loading of the specimens was accomplished through a system of 10:1 levers to which containers holding lead shot were attached. All tests were therefore of the constant load type.

The testing procedure consisted of inserting the specimen — extensometer assembly into the furnace for about two hours for the purpose of reaching the test temperature, followed by gradual application of the load.

Extensometer readings were recorded upon initial complete application of the full load and periodically thereafter throughout the duration of the tests.

EXPERIMENTAL RESULTS

Creep data were obtained for (a) a series of pure aluminum specimens having a grain size of 12.5 grains/mm (b) two series of aluminum-magnesium solid solution specimens (1.10 atomic percent Mg) having grain sizes of 8.3 grains/mm and 2.4 grains/mm respectively and (c) a series of aluminum-copper dispersion (1.18 atomic percent Cu) specimens having a grain size of 8.3 grains/mm. Previous creep data for (a) a series of pure aluminum specimens having a grain size of 2.5 grains/mm and (b) a series of aluminum-copper dispersion (1.18 atomic percent Cu) specimens having a grain size of 2.2 grains/mm were available for the temperatures of 422°K, 477°K and 528°K and were utilized for comparative purposes during this investigation.

All of the creep data were plotted originally on Cartesian co-ordinates to obtain a value for the secondary creep rate, $\dot{\epsilon}$, for each test. A typical curve is shown in Figure 4.
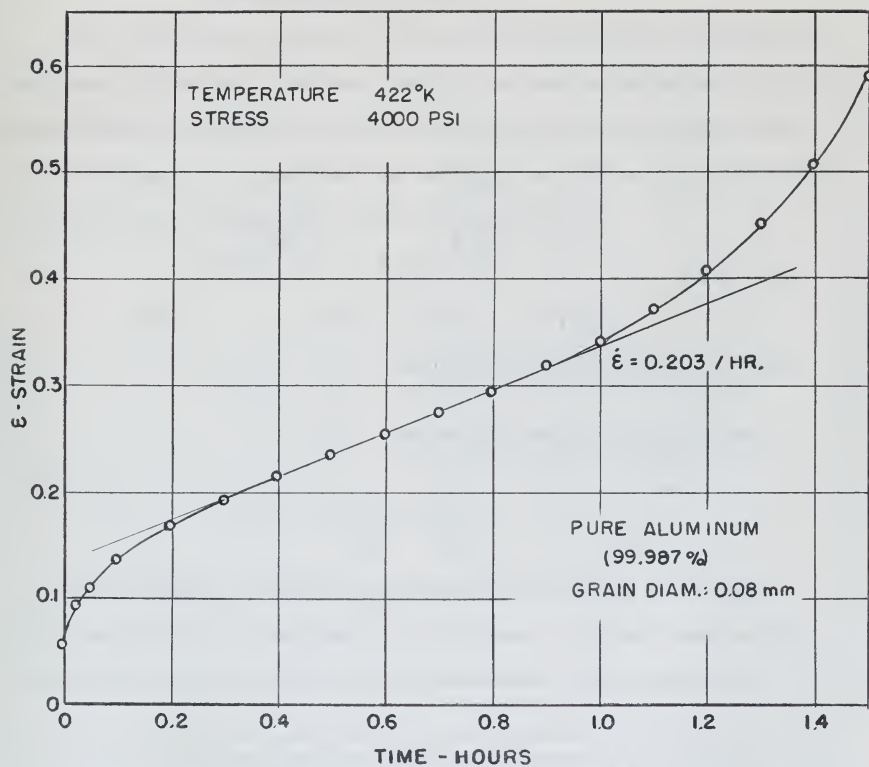
FIG. 4 TYPICAL CREEP CURVE.

For the purpose of condensing the information, the creep data were also plotted as logarithm creep strain versus logarithm time for all of the alloys tested and are illustrated in Figures 5-8.

Values of the stress and test temperatures used in this investigation as well as the calculated secondary creep rate $\dot{\varepsilon}$ are recorded in Table A found in the appendix.

DISCUSSION OF RESULTS

The creep curves (Figures 5-8) for the various alloys investigated exhibited uniform and consistent trends. In order to determine if all the data obtained in this investigation could be correlated by means of the Zener-Hollomon parameter, the energy of activation was determined for each alloy by noting that at the same flow stress

$$\dot{\varepsilon}_1 \, e^{\frac{\Delta H}{R T_1}} = \dot{\varepsilon}_2 \, e^{\frac{\Delta H}{R T_2}}$$

where

ΔH = energy of activation

$\dot{\varepsilon}_1$ = secondary creep rate* for a stress applied at temperature T_1

$\dot{\varepsilon}_2$ = secondary creep rate at the same stress for temperature T_2

or

$$\Delta H = \frac{R \, \ln \frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}}{\left(\frac{1}{T_1} - \frac{1}{T_2} \right)}$$

The calculated energies of activation were found to be 17,000, 21,000 and 18,500 cal/mole for pure aluminum, aluminum-magnesium solid solution, and aluminum-copper dispersion alloys respectively. The

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* Although no physical significance can be attached to the secondary creep rate, it can nevertheless provide a convenient method for cataloguing the behavior of metals and alloys. Therefore in this section, the strain rate employed in calculating ΔH will be taken as the secondary creep rate.
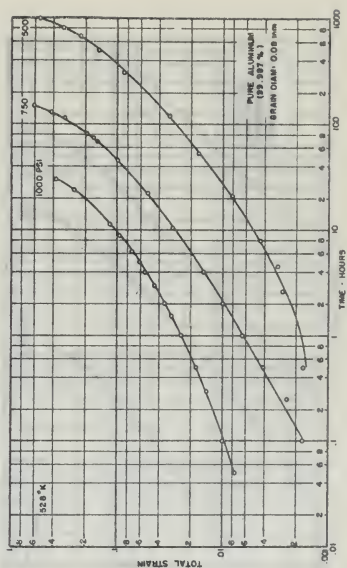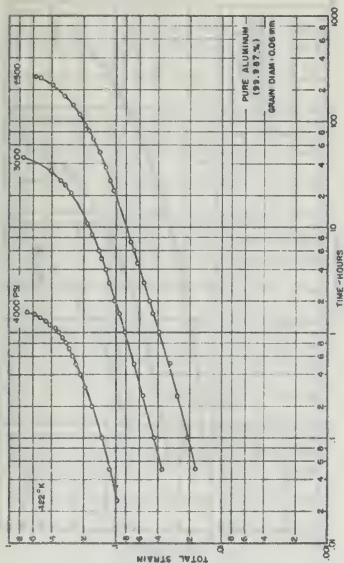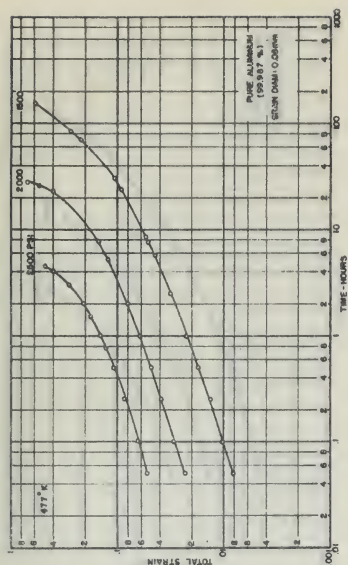
FIG. 5 TOTAL CREEP STRAIN AS A FUNCTION OF TIME FOR HIGH PURITY FINE GRAINED ALUMINUM AT VARIOUS TEMPERATURES.
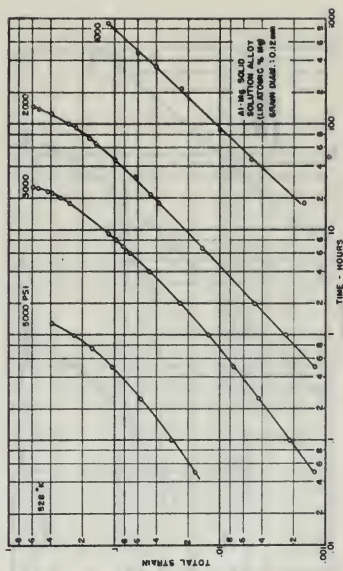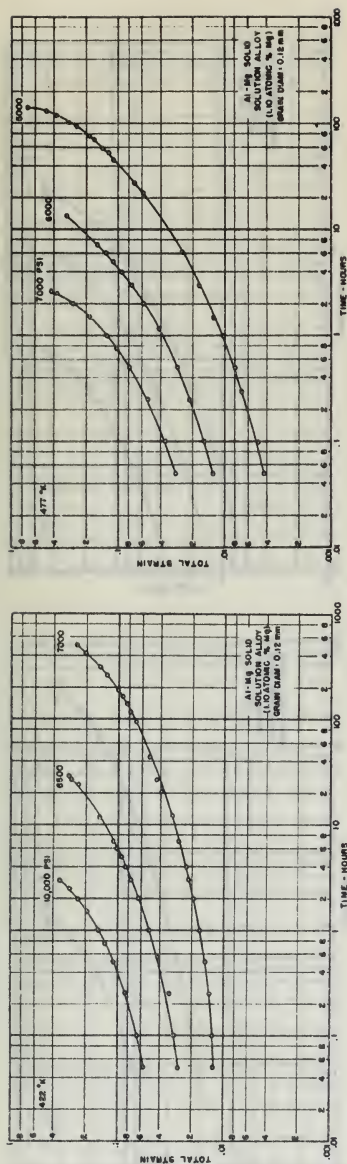
FIG. 6 TOTAL CREEP STRAIN AS A FUNCTION OF TIME FOR FINE GRAINED Al-Mg SOLID SOLUTION ALLOY AT VARIOUS TEMPERATURES.
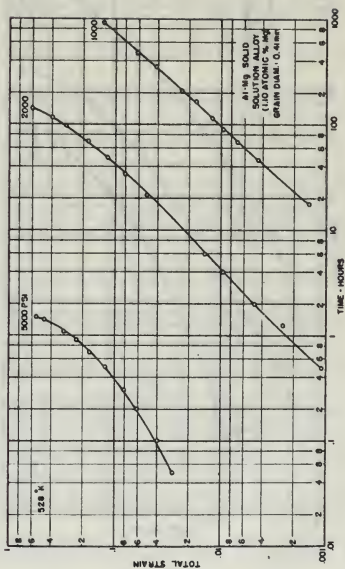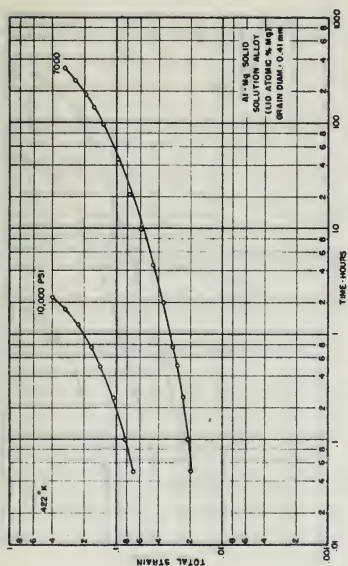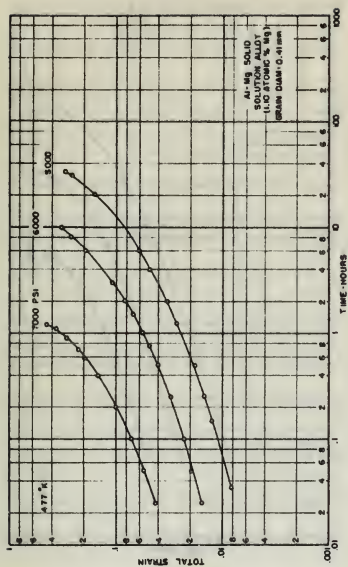
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FIG. 7 TOTAL CREEP STRAIN AS A FUNCTION OF TIME FOR COARSE GRAINED Al-Mg SOLID SOLUTION ALLOY AT VARIOUS TEMPERATURES.
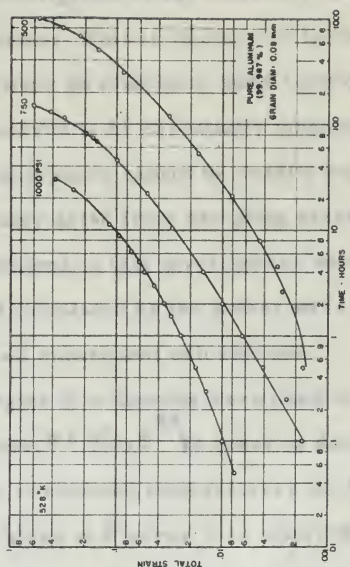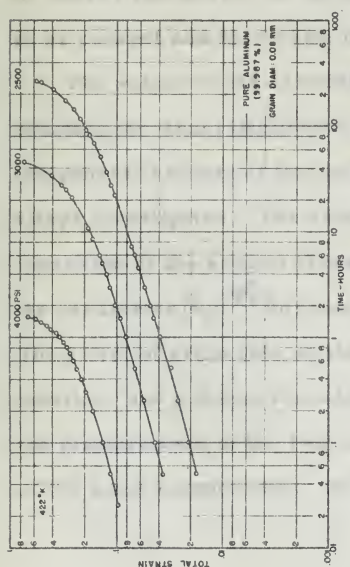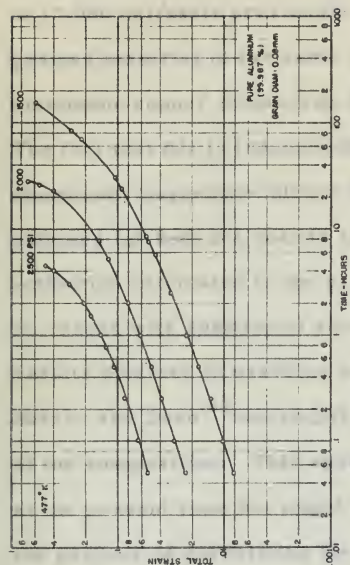
FIG. 5 TOTAL CREEP STRAIN AS A FUNCTION OF TIME FOR HIGH PURITY FINE GRAINED ALUMINUM AT VARIOUS TEMPERATURES.

magnitude of ΔH for the fine grained pure aluminum agrees with the value of 17,000 cal/mole previously obtained by Sherby and Dorn[16] for coarse grained material of the same composition. The appropriate ΔH for the aluminum-copper dispersion alloys for both grain sizes is 18,500 cal/mole. The fact that ΔH is independent of the grain size is also shown by the aluminum-magnesium alloys in that the value of ΔH of 21,000 cal/mole was obtained for both the coarse and fine grained material. The energies of activation calculated in the present investigation show, however, that ΔH increased with addition of solute elements. This is in contrast to the results obtained in previous investigations on aluminum solid solutions by Sherby and Dorn[8] where ΔH was observed to be essentially independent of the composition. This apparent discrepancy cannot be readily explained at the present time but might conceivably arise from sampling errors. For the purpose of correlating the data obtained in this investigation with that of Sherby and Dorn, the values of ΔH calculated by the author were assumed to be correct and have been used for all subsequent calculations.

The values of the calculated energies of activation were used to evaluate the Zener-Hollomon parameter, $\sigma \cong \sigma\left(\dot{\varepsilon}_s e^{\frac{\Delta H}{RT}}\right)$ in order to determine the general validity of this parameter at elevated temperatures for the alloys investigated. The results are given in Figures 9-11 where the logarithm of the applied stress, σ, is plotted against the logarithm of the parameter $\left(\dot{\varepsilon}_s e^{\frac{\Delta H}{RT}}\right)$ for pure Al, Al-Mg, and Al-Cu alloys respectively. The effect of grain size on the creep properties of a pure metal, a solid solution, and a dispersion alloy, however, is very small and is shown by the displacement of the two curves for the fine and coarse grained materials of the same composition. Nevertheless, at low temperatures (large values of
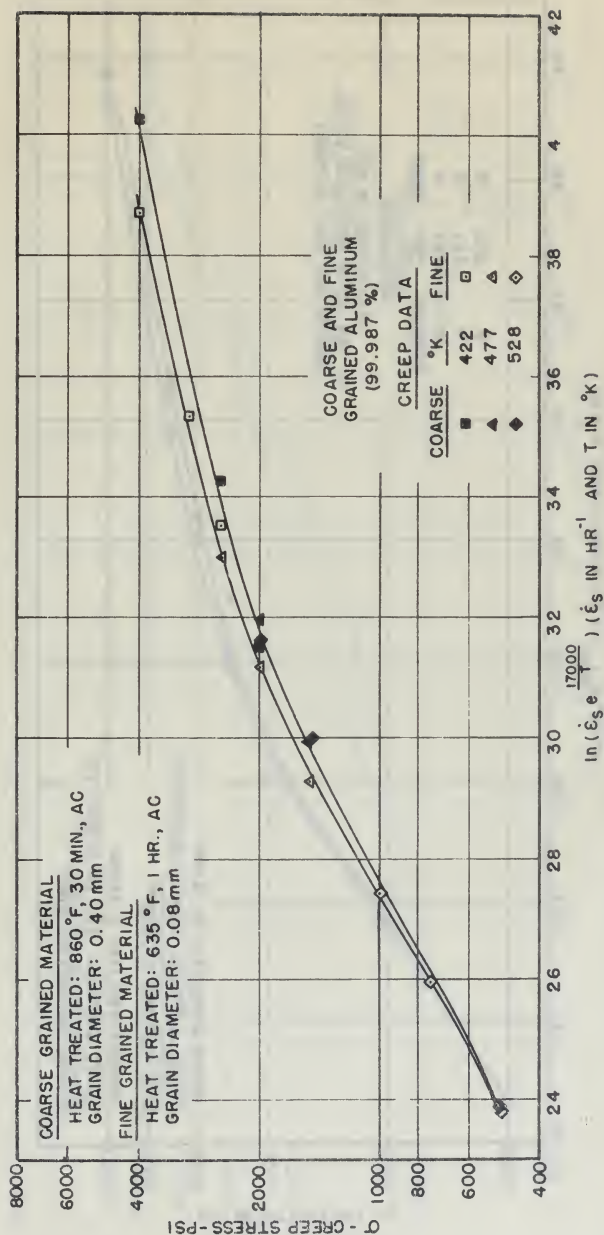
FIG. 9 CORRELATION OF CREEP DATA OF HIGH PURITY ALUMINUM AT VARIOUS TEMPERATURES BY THE EQUATION: $\sigma \equiv \sigma' (\dot{\varepsilon}_s e^{\frac{17000}{T}})$
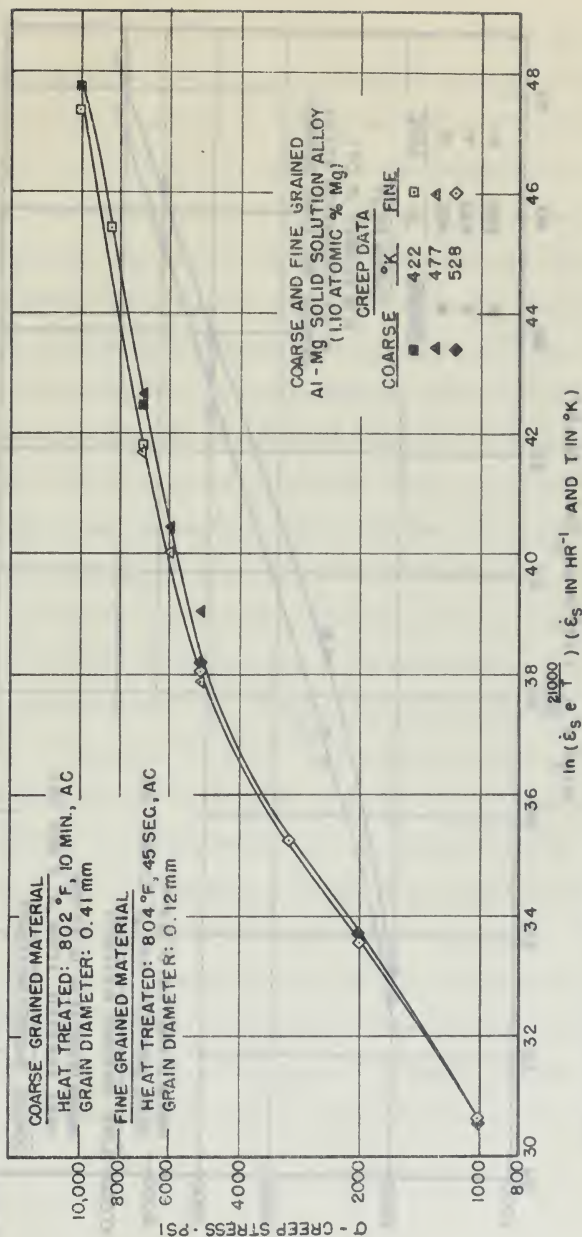
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FIG. IO CORRELATION OF CREEP DATA OF Al-Mg SOLID SOLUTION ALLOY AT VARIOUS TEMPERATURES
BY THE EQUATION: $\sigma \equiv \sigma \left(\dot{\varepsilon}_s e^{\frac{21000}{T}} \right)$

COARSE AND FINE GRAINED
Al - Mg SOLID SOLUTION ALLOY
(1.10 ATOMIC % Mg)

CREEP DATA

COARSE	°K	FINE
■	422	◻
▲	477	△
◆	528	◇

COARSE GRAINED MATERIAL
  HEAT TREATED: 802 °F, IO MIN., AC
  GRAIN DIAMETER: 0.41 mm

FINE GRAINED MATERIAL
  HEAT TREATED: 804 °F, 45 SEC., AC
  GRAIN DIAMETER: 0.12 mm

$\ln \left(\dot{\varepsilon}_s e^{\frac{21000}{T}} \right)$ ($\dot{\varepsilon}_s$ IN HR^{-1} AND T IN °K)
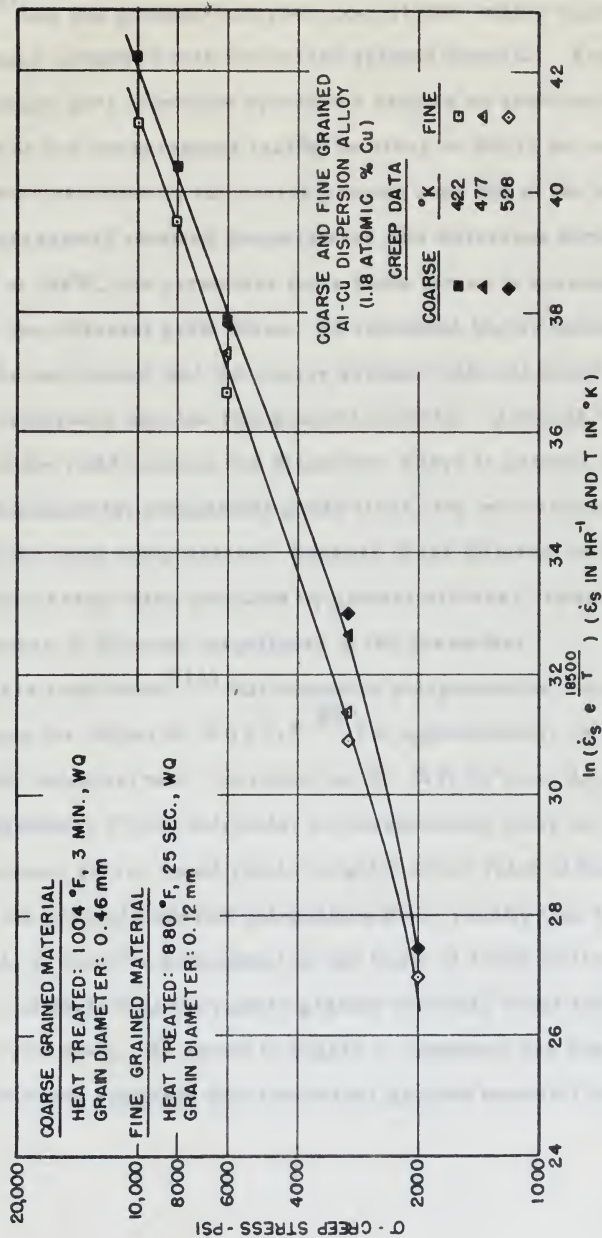
σ - CREEP STRESS - PSI

20

FIG. 11 CORRELATION OF CREEP DATA OF AI-C DISPERSION ALLOY AT VARIOUS TEMPERATURES

BY THE EQUATION: $\sigma \equiv \sigma \left(\dot{\epsilon}_s e^{\frac{18500}{T}} \right)$

COARSE AND FINE GRAINED
AI-Cu DISPERSION ALLOY
(1.18 ATOMIC % Cu)

CREEP DATA

	°K	FINE	COARSE
	422	⬜	◼
	477	▲	▲
	528	◇	◆

$\ln \left(\dot{\epsilon}_s e^{\frac{18500}{T}} \right)$ ($\dot{\epsilon}_s$ IN HR^{-1} AND T IN °K)

COARSE GRAINED MATERIAL
HEAT TREATED: 1004 °F, 3 MIN., WQ
GRAIN DIAMETER: 0.46 mm

FINE GRAINED MATERIAL
HEAT TREATED: 880 °F, 25 SEC., WQ
GRAIN DIAMETER: 0.12 mm

σ - CREEP STRESS - PSI

$\varepsilon_s e^{\frac{\Delta H}{RT}}$, the fine grained materials consistently exhibit superior creep resistance compared with the coarse grained material. For example, the fine grained pure aluminum specimens require an additional stress of about 150 psi at low temperatures ($422°K$) in order to obtain the value of the parameter exhibited by the coarse grained material at the same temperature. At progressively elevated temperatures this difference diminishes until finally at $528°K$, the parameter for a given stress is essentially identical for the two different grain sizes. At somewhat higher temperatures, it might be anticipated that the coarse grained material would exhibit greater creep resistance than the fine grained material. Although the creep resistance of the solid solution and dispersion alloys is greater than that for pure aluminum for comparable grain sizes, the inversion occurs at approximately the same temperature. Because of the differences in ΔH and the secondary creep rates produced by greater stresses, however, the inversion occurs at different magnitudes of the parameter.

It has been shown[16] that extensive polygonization occurs in pure aluminum for values of $\ln\left(\dot{\varepsilon}_s e^{\frac{\Delta H}{RT}}\right)$ of approximately 34 for a ΔH of 17,900 calories/mol. Inasmuch as the ΔH for pure Al used in this investigation is 17,000 cal/mole, a corresponding value of $\ln\left(\dot{\varepsilon}_s e^{\frac{\Delta H}{RT}}\right)$ for the same stress would yield a slightly lower value of the parameter. If the fine grained material polygonizes more readily than the coarse grained, it would be anticipated on the basis of shear and/or polygonization and shear that the coarse grained material would exhibit superior creep resistance. As shown in Figure 9, however, the fine grained material is more creep resistant than the coarse grained material for a value of

$\ln (\dot{\varepsilon}_s e^{\frac{\Delta H}{RT}})$ of about 34. On the other hand, apparent merit for the polygonization theory seems to have been obtained when the temperature of inversion for the coarse and fine grained solid solutions and dispersions are compared with pure Al. For example, the temperature of inversion for solid solutions of Al-Mg and pure Al are identical while that of the dispersion seems to be at a higher temperature.

On the basis of the model proposed by Chang and Grant, the increased resistance to creep of solid solution and dispersion alloys compared with pure Al seems to be attributable partly to the decreased rate of migration of the boundaries and partly to the increased stress necessary to induce grain boundary shear.

The preceding discussion has been restricted to a correlation of the grain size effect of the three materials investigated and is based on the thought that the secondary creep rate could be used to catalogue their behavior with temperature and stress. It has been shown for pure aluminum and its solid solutions, however, that the total strain in a creep test can be correlated with the time and temperature of that test provided the load is maintained constant. This was accomplished with the present data by plotting the strain versus a "temperature corrected time", $t e^{-\frac{\Delta H}{RT}}$. The data from this investigation have been plotted in accordance with this parameter in Figures 12 and 13. The resultant plots indicate that this type of correlation is valid not only for various grain sizes of pure aluminum and its solid solutions but is also applicable to the more complex dispersion alloys. The slight variations noted in the creep curves for material of the same composition under the same stress but at different
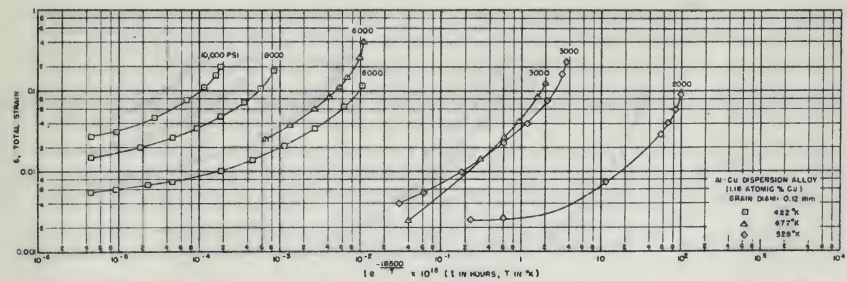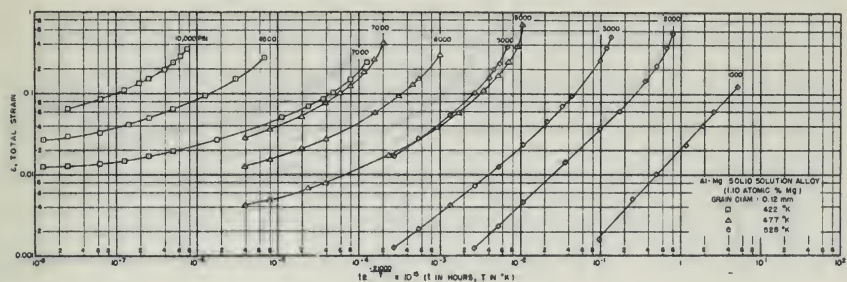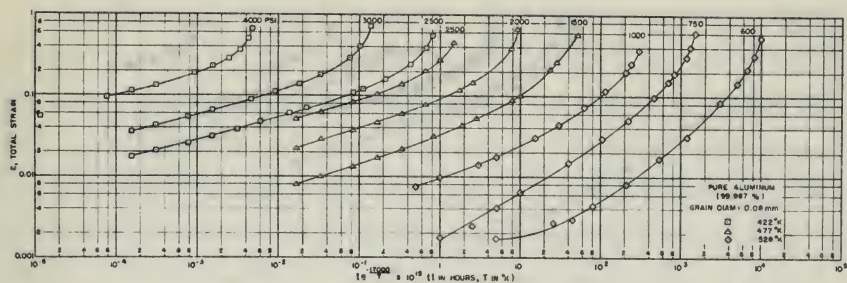
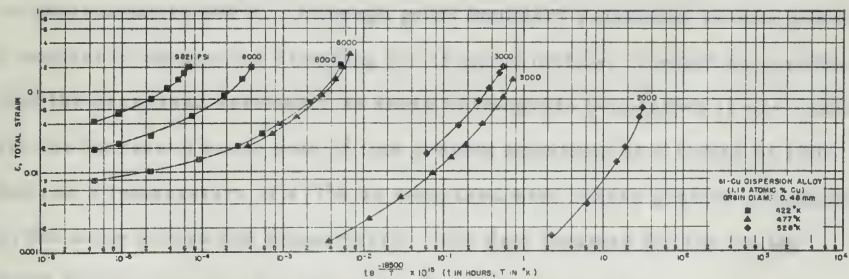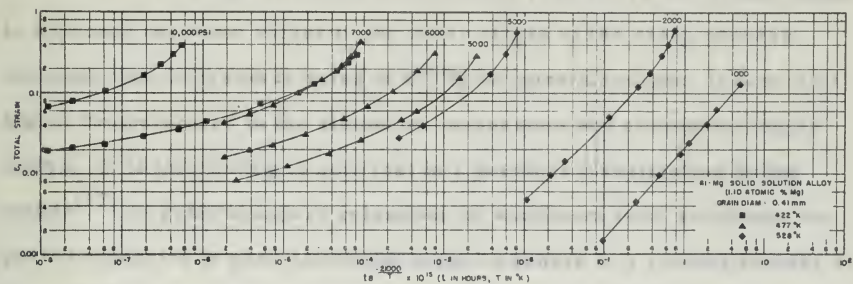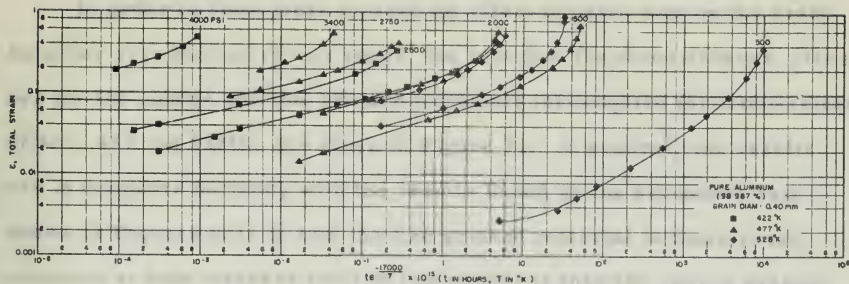FIG. 12 CORRELATION OF CREEP STRAIN - TIME DATA OF VARIOUS FINE GRAINED ALLOYS OF ALUMINUM BY THE EQUATION $\varepsilon = \varepsilon (te^{-\frac{\Delta H}{RT}})$.

FIG 13 CORRELATION OF CREEP STRAIN - TIME DATA OF VARIOUS COARSE GRAINED ALLOYS OF ALUMINUM BY THE EQUATION: $\varepsilon = \varepsilon \left(t e^{-\frac{\Delta H}{RT}} \right)$.

temperatures is believed to originate in sampling and experimental errors or in differences in the values of ΔH, rather than in failure of the temperature corrected time concept.

In order to show more clearly the effect of grain size on the creep behavior over the entire test range, the test data for three different stresses for the coarse and fine grained materials investigated for temperatures of 422, 477 and 528^0K. are given in Figure 14. In general, the results are in complete harmony with the results based on the secondary rate shown in Figures 9-11 in that the fine grained material is more creep resistant at high stresses and low temperatures than the coarse grained material. At the higher testing temperatures, however, the strains began to approach the same values in the latter stages of the creep process. Although this inversion is noted at 477^0K for pure aluminum, it occurs at higher temperatures in the aluminum-magnesium and aluminum-copper alloys. It is interesting to note that in a previous investigation by the author[17] on grain boundary relaxation of aluminum solid solutions, the grain boundaries in pure aluminum began to behave in a viscous manner at about 453^0K. Additions of magnesium, however, raised this temperature to approximately 490^0K. Although grain boundary relaxation is only one of a number of phenomena attending the creep of metals, it might be possible that the decreased resistance to shear of the grain boundaries is one cause for the increased creep rate of fine grained aluminum at a stress of 1500 psi and a temperature of 477^0K as compared with coarse grained aluminum at the same stress and temperature. The data obtained for the Al-Mg solid solution alloy are also in accord with this postulate.
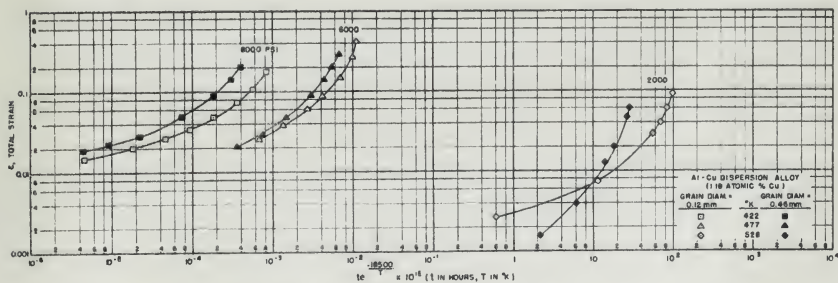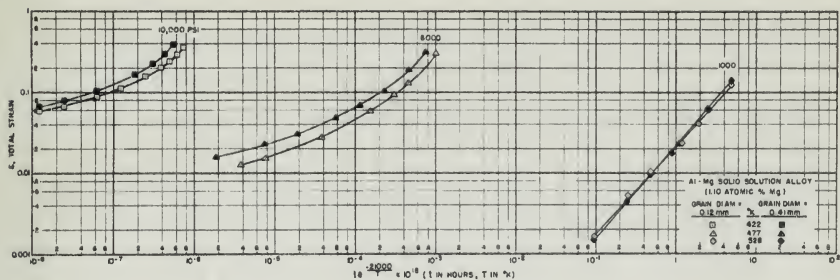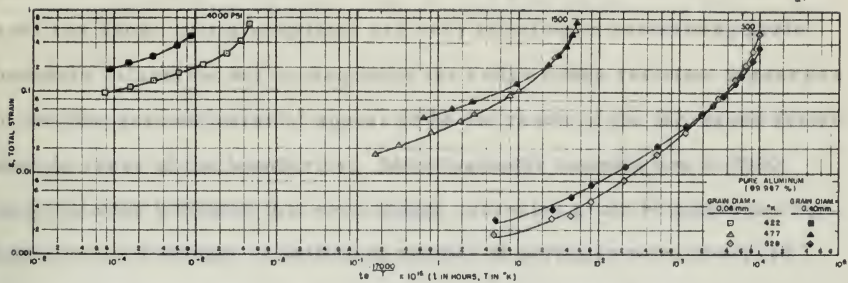
FIG. 14 CORRELATION OF CREEP STRAIN -TIME DATA OF FINE AND COARSE GRAINED HIGH PURITY ALUMINUM AND ALUMINUM ALLOYS

BY THE EQUATION $\varepsilon = \varepsilon (1 e^{-\frac{\Delta H}{RT}})$.

The aluminum-copper alloys show the same general trends with the exception that at high temperatures (528°K) and large strains the fine grained material is stronger than the coarse grained material. Kê, however, has shown that precipitates are very effective in restraining grain boundary relaxation and consequently the better creep resistant properties of the fine grained material appear to be the result of the increased resistance to shear of the boundaries. Metallographic examination at 2000 magnification indicated that even though excessive grain boundary precipitation was not evident, a sufficient number of particles were observed along the boundary which could restrain grain boundary shear.

SUMMARY AND CONCLUSIONS

1. Creep tests have been performed on pure aluminum, aluminum-magnesium solid solution and aluminum-copper dispersion alloys at temperatures of 422^0K, 477^0K and 528^0K.

2. There is a minor grain size effect on the creep behavior of the metals investigated. Creep data for pure aluminum, aluminum-magnesium solid solution and aluminum-copper dispersion alloys show fine grained material superior to coarse-grained material at low temperatures and high stresses.

3. The creep behavior exhibited by fine and coarse grained material of a specific composition is essentially the same at about 528^0K when comparison is made on the basis of secondary creep rate considerations.

4. The value of ΔH varies for the alloys investigated. The value of ΔH for pure aluminum was found to be 17,000 cal/mole, aluminum-magnesium, 21,000 cal/mole and aluminum-copper, 18,500 cal/mole.

5. The observed behavior of the materials studied can be explained on the basis of grain boundary migration and shear. This, however, might not be the only process.

6. The parameter $\ln\left(\dot{\epsilon}_s e^{\frac{\Delta H}{RT}}\right)$ can be used to correlate the creep behavior of pure metals, solid solution and dispersion alloys.

ACKNOWLEDGMENT

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APPENDIX

<u>TABLE A</u>

Material	Grain Size (grains/mm)	Temperature (^{0}K)	Stress (psi)	$\dot{\varepsilon}$
Aluminum (99. 987% Al)	2.5	422	2,000 2,500	0.0001595 0.00244
		477	1,500 2,000 2,750	0.002125 0.02425 0.3820
		528	500 1,500 2,000	0.000237 0.1091 0.5090
	12.5	422	2,500 3,000 4,000	0.0012 0.00733 0.203
		477	1,500 2,000 2,500	0.00177 0.0115 0.068
		528	500 750 1,000	0.000224 0.002 0.00836
Al-Mg (1.10 Atomic % Mg)	2.4	422	7,000 10,000	0.00065 0.1245
		477	5,000 6,000 7,000	0.00669 0.0277 0.250
		528	1,000 2,000 5,000	0.0001048 0.00233 0.2051
	8.3	422	7,000 8,500 10,000	0.000341 0.0127 0.090
		477	5,000 6,000 7,000	0.00213 0.0182 0.100

Material	Grain Size (grains/mm)	Temperature (^{0}K)	Stress (psi)	$\dot{\epsilon}$
		528	1,000	0.0001057
			2,000	0.002
			3,000	0.0109
			4,000	0.182
Al-Cu (1.18 Atomic % Cu)	2.2	422	6,000	0.00251
			8,000	0.0323
			9,921	0.187
		477	3,000	0.0021
			6,000	0.376
		528	2,000	0.000514
			3,000	0.132
	8.3	422	6,000	0.000747
			8,000	0.0131
			10,000	0.0676
		477	3,000	0.000595
			6,000	0.229
		528	2,000	0.0005
			3,000	0.0158